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Conceptual Designs and Cost Estimates for E-SOx Retrofits to Coal-Fired Utility Power Plants

Gilbert/Commonwealth, Inc., Reading, PA

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CONCEPTUAL DESIGNS AND COST ESTIMATES FOR E-SO_X RETROFITS TO COAL-FIRED UTILITY POWER PLANTS

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16. ABSTRACT The report describes a conceptual design and cost estimate, based on information available at the beginning of 1987, for six cases of a retrofit of the E-SOx process to a utility. The annualized cost ranged from $301 to $378 per ton of SO2 removed. The generic cost basis, used for other cost estimates, was used in this study and applied to a 500 MWe utility burning eastern medium-sulfur (2.5%) bituminous coal. Capital costs compare very favorably with other retrofit SO2 removal technologies. Sorbent or reagent cost is the largest single component of the costs.

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Abstract

A conceptual design and cost estimate, based on information available at the beginning of 1987, was done for six cases of a retrofit of the E-SO_x process to a utility. The annualized cost in dollars per ton of SO_2 removed ranged from $301 to $378. The generic cost basis, used for other cost estimates, was used in this study and applied to a 500 MWe utility burning eastern medium sulfur (2.5%) bituminous coal. Capital costs compare very favorably with other retrofit SO_2 removal technologies. Sorbent or reagent cost is the largest single component of the costs.

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1.0 EXECUTIVE SUMMARY

1.1 Background

E-SOX technology has been proposed as a feasible means of lowering sulfur oxide emissions from power plants upon retrofit to an existing electrostatic precipitator. Accordingly, Gilbert/Commonwealth, Inc. (G/C) has performed a conceptual study to evaluate various retrofit situations. In so doing, applicable bases were kept identical with a similar study conducted in 1983 concerning Limestone Injection Multistage Burner (LIMB) systems, reported on in Reference 1.

The conceptual designs discussed herein are based on a "generic" power plant. All subsystems necessary for a complete E-SOX system are included in the costs. Optimizations of equipment and systems were performed on a limited basis, as this is not a site-specific study. Thus, costs will vary from those presented here, as specific locations are considered. The study does provide a point of reference for comparison purposes, and shows where future research and development efforts should be concentrated.

1.2 Scope and Approach

Following the LIMB study, plant size was selected as 500 MW, with existing particulate control equipment designed to meet the 1971 New Source Performance Standards for particulate matter. The process designs were based on lime stoichiometries and approach temperatures necessary to achieve 50 percent sulfur reduction for a typical eastern, medium sulfur (2.5%) bituminous coal. Two process conditions were selected using hydrated lime as a reagent, and one using quicklime. For one of the lime hydrate process conditions, four different precipitator upgrade configurations were evaluated. A total of six E-SOX cases were investigated. These are summarized below.

Case 1 - Hydrated lime reagent, Ca/S = 1.3, approach temperature 40°F, original 218 SCA ESP, retrofitted with precharger and large diameter electrodes.

Case 2 - As Case 1 with the exceptions of no precharger, weighted wires instead of large diameter discharge electrodes, and 1.5-ft. longer collecting plates in each field.

Case 3 - As Case 1 with the exceptions of original 150 SCA ESP, plate height increased by 3-ft. and collecting plates in each field increased in length by 1.5-ft.

Case 4 - As Case 3 with the exceptions of no precharger, weighted wires instead of large diameter discharge electrodes, and an additional short third active field.

Case 5 - As Case 1 with the exceptions of a Ca/S ratio of 1.5 and an approach temperature of 50°F.

Case 6 - As Case 1 with the exception that pebble quicklime is used as a reagent.

The study consisted of the conceptual equipment selection, equipment arrangement and capital and first year operating and maintenance cost estimates for the E-SOX system and all supporting equipment for the above six cases.

1.3 Findings

The mechanical equipment used as a basis for these designs is predominantly commercial. Lime receiving and storage and slurry preparation are state-of-the-art for many existing scrubbers, both wet and dry. On the other hand, the two fluid nozzle arrangement, because of its requirement for a relatively flat and fine droplet size distribution (40-50 μm), requires some developmental work. Also some of the chosen precipitator modifications, which use

advanced technology to achieve the required particulate removal, as exemplified by the precharger and large-diameter electrodes, require developmental work. Hence, there is more uncertainty in the precipitator performance of Cases 1, 3, 5, and 6 than in the Cases 2 and 4, which are more conventional ESP upgrades. Because there is limited laboratory scale process data available, there are process uncertainties associated with reagent stoichiometry, approach temperature, and residence time. The latter also raises the question of whether adequate spray drying can occur without wetting the precipitator.

Concerning precipitator performance for the E-SOX process, computed ESP collection efficiency and particulate mass emissions are tabulated for each case in Table 1-1. ESP performance was assessed by Southern Research Institute using its ESP Mathematical Model. A comparison of Cases 1 and 2 shows that a modest increase in plate length will achieve the same ESP performance improvement as the installation of novel electrodes. With low-resistivity fly ash and reasonable plate area after an E-SOX retrofit (SCA of 173 $ft^2/1000$ acfm prior to ESP modifications) the precharger offers little performance advantage. It accomplishes quickly the dust particle charging that otherwise would be accomplished within 2 or 3 feet of travel along a conventional gas passage. The large-diameter discharge electrodes, on the other hand, offer a performance advantage due to the increased interelectrode electric field. In Cases 3 and 4, with a much lower plate area after an E-SOX retrofit (SCA of 118 $ft^2/1000$ acfm prior to ESP modifications), a substantial re-build of the ESP is required to limit particulate emissions to 0.1 $lb/10^6$ Btu.

TABLE 1-1

PRECIPITATOR PERFORMANCE

	Case No.					
	1	2	3	4	5	6
SCA (sq. ft/1000 ACFM)	173	201	163	148	171	172
Outlet Emissions, lb/10^6 Btu	0.08	0.08	0.08	0.07	0.08	0.08
Collection Efficiency, %	99.59	99.56	99.57	99.62	99.57	99.58

A summary of the capital and O&M costs for the six E-SOX cases is provided in Table 1-2. The capital costs compare very favorably with other retrofit SO_2 removal technologies. This is attributed to the maximum use of existing equipment and minimal new equipment requirements. First year O&M costs are largely influenced by lime consumption and delivered cost.

As a means to compare overall costs of the systems, Table 1-3 presents total first year costs on an annualized basis, as well as costs per ton of SO_2 removed. The costs per ton of SO_2 removed indicate that E-SOX technology, if it can be successfully commercialized, should compete very favorably with other retrofit SO_2 removal technologies.

TABLE 1-2

COST SUMMARY
(January 1987 Dollars)

Case No.	Capital Cost		First Year Operating and Maintenance Cost	
	$1000	$/kW	$1000/YR	Mills/kWh
1	19,100	38	6,800	2.39
2	23,700	47	6,980	2.45
3	22,700	45	6,940	2.44
4	19,400	39	6,890	2.42
5	19,100	38	7,480	2.62
6	15,900	32	6,070	2.13

TABLE 1-3

FIRST YEAR ANNUALIZED COSTS ($1000/YR)
(January 1987 Dollars)

	Case No. 1	2	3	4	5	6
Annualized Capital Cost	3,440	4,260	4,090	3,500	3,440	2,870
First Year O&M Cost	6,800	6,980	6,940	6,890	7,480	6,070
Total First Year Annualized Cost	10,240	11,240	11,030	10,390	10,920	8,940
$/ton SO_2 Removed	345	378	371	350	368	301

In summary, the following conclusions can be drawn:

- The mechanical system design for the most part utilizes commercially available equipment. The only items that pose developmental problems are the two fluid nozzle spray system, the ESP precharger, and the ESP large diameter electrodes.

- From an operating point of view, the greatest concern is adequate spray drying in the (gutted) first field of the ESP to minimize tenacious deposits in the subsequent ESP fields.

- ESP performance on this type of particulate needs to be verified. In particular, the mass loadings and size distribution of the particulate at the end of the spray section, the ESP electrical properties (secondary voltages and currents), and gas distribution device requirements need to be established.

- The capability of a vacuum type flyash handling system to continuously remove hopper material needs to be demonstrated. Additional equipment requirements (for example a delumper to prevent oversize material) need to be defined.

- Retrofit capital costs will be very site specific, particularly if conventional ESP modifications (taller plates or an outlet field) are required.

- The largest single component affecting the operating cost is the reagent consumption. Therefore, process stoichiometry is critical to cost. Also, pebble lime shows a distinct economic advantage over lime hydrate.

- Future research efforts should be concentrated on optimizing the process parameters, in particular, slurry droplet size,

Ca/S ratio, approach temperature, and residence time requirements.

- Because of the performance advantages indicated by the precharger and large diameter electrodes, these technologies should be further demonstrated at an appropriate equipment scale.

2.0 INTRODUCTION

Much research has been performed in recent years on the concept of dry scrubbing for SO_2 removal. One of the more novel schemes employing dry scrubbing is the E-SOX process. In this process, the dry scrubbing operation is performed in a power plant's electrostatic precipitator. To gain space for the injection equipment, the first field of the precipitator has all active internals removed. Although this is normally a measure that would lower the precipitator's collection efficiency, the reagent slurry "conditions" the flue gas so that the original performance level is at least partially recovered.

This report documents a study performed by Gilbert/Commonwealth, Inc. (G/C), to provide an engineering evaluation for retrofit of the E-SOX process to a commercial size utility power plant. Lime is used as the reagent. This evaluation parallels a study previously conducted by G/C focusing on the Limestone Injection Multistage Burner (LIMB) technology (Reference 1) thus providing a basis for comparison between the two processes.

As in the LIMB study, reagent stoichiometries were chosen based on laboratory-scale test data to remove 50 percent of the SO_2 from the flue gas. From this data, it appears that a calcium-to-sulfur ratio of 1.3 can achieve this removal when the flue gas is cooled to within 40°F of the adiabatic saturation temperature. This is the base case for this study, although one case is also considered using a Ca/S ratio of 1.5 and an approach temperature of 50°F. The retrofit is applied to a "generic" 500 MW unit burning a "typical" eastern 2.5 percent sulfur bituminous coal.

In addition to fitting reagent injection equipment into the first precipitator field, modifications must be made to the remaining fields in order to stay below particulate emission limits. Some of these modifications include the use of prechargers ahead of the active precipitator fields, use of large diameter discharge

electrodes, and an increase in collecting plate area. The various precipitator modifications provide a measure for cost/benefit to achieve the required particulate removal. The various cases considered are as follows:

Case 1 - Hydrated lime reagent, Ca/S = 1.3, approach temperature 40°F, original 218 SCA ESP, retrofitted with precharger and large diameter electrodes.

Case 2 - As Case 1 with the exceptions of no precharger, weighted wires instead of large diameter discharge electrodes, and 1.5-ft. longer collecting plates in each field.

Case 3 - As Case 1 with the exceptions of original 150 SCA ESP, plate height increased by 3-ft. and collecting plates in each field increased in length by 1.5-ft.

Case 4 - As Case 3 with the exceptions of no precharger, weighted wires instead of large diameter discharge electrodes, and an additional 3-ft. long field.

Case 5 - As Case 1 with the exceptions of a Ca/S ratio of 1.5 and an approach temperature of 50°F.

Case 6 - As Case 1 with the exception that pebble quicklime is used as a reagent.

The study consisted of the conceptual equipment selection, equipment arrangement and cost estimate for the E-SOX system and supporting equipment. Gilbert/Commonwealth's scope of work and approach consisted of the following tasks:

1. Develop the technical requirements, and the process and equipment design bases for the E-SOX system.

2. Technically and economically screen the available equipment options and conceptually design the E-SOX system. The additional equipment includes reagent unloading, storage, transfer, and slurry preparation; atomizing air compressors and piping; slurry injection pumps and piping; additional solids disposal equipment; and associated civil/structural, electrical, and controls.

3. Identify and estimate costs of the major modifications to existing equipment.

4. Identify conceptual equipment locations and arrangement for a "typical" retrofit scenario.

5. Prepare preliminary process flow diagrams, system descriptions, equipment lists, and general arrangement drawings for the conceptual designs.

6. Obtain vendor budget price estimates for major equipment items.

7. Develop capital cost estimates for those items not quoted by equipment vendors, based on the descriptions, lists and diagrams developed for this study.

8. Identify major operating and maintenance costs for the system.

9. Provide a report summarizing the conceptual E-SOX system design and cost estimate for the six design cases.

Southern Research Institute assisted in the study by identifying various engineering uncertainties that presently exist in the E-SOX technology and by performing mathematical modeling to establish the ESP retrofit configurations needed for each case. The technical issues that were addressed by SRI included:

- changes in dust particle size distribution
- changes in dust particle mass loading
- dust particle precharging
- collecting electrode modifications
- discharge electrode modifications
- improvements in gas flow uniformity
- reductions in gas sneakage
- suppression of rapping reentrainment

The study resulted in a more detailed understanding of needs for pilot-scale R&D work before proceeding to a full-scale demonstration of E-SOX technology. A summary of these needs is included in the Results and Conclusions.

3.0 DESIGN BASIS

3.1 Process Design

General technical design criteria and assumptions used in the conceptual process design are as follows:

a. A single coal is used for all six cases. This is a medium sulfur eastern bituminous (2.5% S) with proximate and ultimate analyses as shown in Table 3-1. All of the coal sulfur content is assumed converted to SO_2.

b. The ash analysis for the Base Case coal is shown in Table 3-2.

c. Required SO_2 removal is 50 percent.

d. Flyash emission limit is 0.1 lb flyash/million Btu. Flyash emission limits are assumed to be the same both with and without retrofit of E-SOX.

e. Overall excess air leaving the air heater and entering the ESP is 40 percent. This includes excess combustion air, casing in-leakage, and air heater leakage.

f. Flue gas temperature at the air heater outlet is assumed to be 310°F.

g. Flyash-to-bottom ash ratio is 80/20.

h. Coal consumption is based on a 500 MW unit and an assumed plant heat rate of 10,000 Btu/kWh or 5×10^9 Btu/hr boiler heat input.

TABLE 3-1

COAL ANALYSIS

Coal Source - Medium Sulfur Eastern Bituminous	As Received Analysis
Proximate Analysis, Weight Percent	
Moisture	3.0
Volatile Matter	32.0
Fixed Carbon	50.0
Ash	15.0
Total	100.0
HHV, Btu/lb	12,000
lb $SO_2/10^6$ Btu	4.17
lb Ash/10^6 Btu	12.5
Ultimate Analysis, Weight Percent	
Moisture	3.0
Hydrogen	4.2
Carbon	68.3
Sulfur	2.5
Nitrogen	1.2
Oxygen	5.8
Ash	15.0
Total	100.0

TABLE 3-2

ASH ANALYSIS

Component	Wt %
SiO_2	48.6
Al_2O_3	26.6
Fe_2O_3	12.7
CaO	2.0
MgO	0.7
Na_2O	0.4
K_2O	2.1
TiO_2	1.5
P_2O_5	1.9
SO_3	0.3
	96.8
Base/Acid	0.23
Fe_2O_3/CaO	6.35
SiO_2/Al_2O_3	1.83

i. The reagent is assumed to be either hydrated lime produced from a high-calcium quicklime (98% $Ca(OH)_2$) or pebble quicklime (92% CaO).

j. Calcium-to-sulfur mole ratio based on inlet SO_2 for 50 percent SO_2 removal from laboratory test results is 1.3 at an approach temperature of 40°F and 1.5 at an approach temperature of 50°F.

k. Flue gas data is based on a plant elevation of 1,000 feet above sea level.

l. Makeup water is assumed readily available at 60°F.

m. Reaction product is assumed to be 100 percent $CaSO_3 \bullet 1/2\ H_2O$.

n. Emissions limitation is 0.1 lb particulate per million Btu heat input.

3.2 Equipment Design

General technical design criteria and assumptions used in this study include:

a.	Air heater type	Regenerative
b.	Particulate removal	Cold side ESP
c.	Boiler load profile	50 to 100 percent MCR
d.	Capacity factor	65 percent
e.	Reagent delivery method	20 ton pneumatic tanker
f.	Reagent delivery schedule	1 shift/day, 5 days/week

g.	Reagent storage	Closed silos, 30-day capacity, 6 silos for hydrated lime, 2 silos for pebble lime.
h.	Reagent bulk density	25 pcf hydrated lime; 55 pcf pebble lime
i.	Reagent transfer	Pneumatic
j.	Reagent intermediate storage	One silo at 24-hour capacity, 445 tons for lime hydrate, 310 tons for pebble lime
k.	Mix tank	One tank at 1-hr. capacity, approx. 20,000 gal.
l.	Slurry transfer pumps	One operating, one spare, 410 GPM at 55 ft. TDH
m.	Slurry recycle tank	One tank at 10-min. capacity, approx. 2,000 gal.
n.	Slurry recycle pumps	One operating, one spare, 700 GPM at 255 ft. TDH
o.	Injection equipment	Two-fluid B&W nozzle; 4.17 GPM at 85 psig slurry pressure; 100 nozzles
p.	Injection point	Inlet of first ESP field

q.	ESP modifications	Various for different cases; see Section 4.3
r.	Atomizing air compressors	Two 50% capacity; 9,000 SCFM at 110 psig; 2000 hp each
s.	Flyash system modifications	Additional vacuum system, 50 TPH

4.0 SYSTEM DESCRIPTIONS

4.1 Process Description

As one method of controlling SO_2 emissions from power plants, experiments have been run in laboratory scale equipment on a process combining advanced electrostatic precipitator and spray dryer technologies to remove both particulate and SO_2 in the same piece of equipment. In the E-SOX process, the inlet field of the ESP is gutted and replaced with a matrix of spray nozzles which serve to introduce a reagent slurry of milk of lime which reacts with the SO_2 in the flue gas and precipitates out as a dry powder. This powder is removed in the active precipitator fields along with the fly ash. The water in the slurry evaporates, cooling the flue gas to a level designed to approach the adiabatic saturation temperature as closely as possible, since this results in maximum SO_2 removal. Because some finite margin is necessary for operating upsets, the approach temperature is limited in this study to a minimum of 40° F above the adiabatic saturation temperature.

Another parameter affecting SO_2 removal is the calcium-to-sulfur ratio. A review of the literature (References 2, 3, 4, and 5) indicates that 50 percent removal is achievable with a Ca/S ratio of 1.3 at a 40° F approach temperature and a mean droplet diameter in the 40 to 50 micron range. At least two manufacturers claim their nozzles produce a spray of this type. Compressed air is required for atomization.

The process flow diagram for the Base Case, without E-SOX, is shown in Figure 4-1 and the material balance in Table 4-1. The process flow diagram for E-SOX Cases 1 through 5 is presented in Figure 4-2 with the corresponding material balances in Table 4-2 (Cases 1-4) and Table 4-3 (Case 5). The Case 6 flow diagram and material balance are shown in Figure 4-3 and Table 4-4, respectively.

BASE CASE	MADE	GILBERT ASSOCIATES, INC. ENGINEERS AND CONSULTANTS READING, PENNA.
FLOW DIAGRAM	CHK'D.	
FIGURE 4-1	DD. EP.	
	EP. SPVR.	
	ENG.	WORK ORDER / DWG. / DRAWING / REV.
	DEV. CH. APP. DATE	

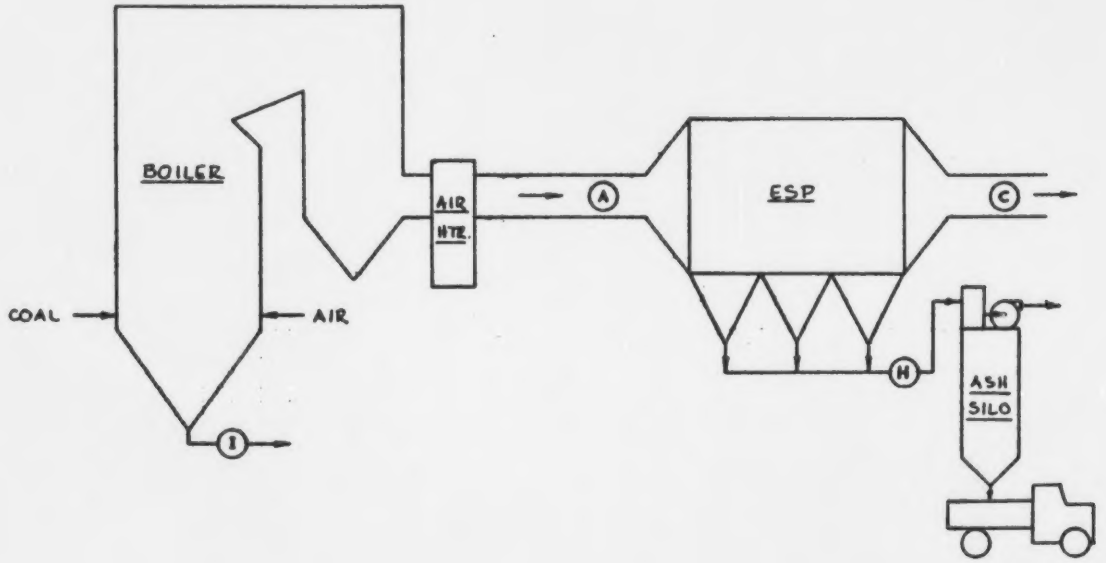

TABLE 4-1

MATERIAL BALANCE

BASE CASE (w/o E-SOX)

	Stream A	Stream C
Mass Flow (Gas), Lb/Hr	5,750,000	5,750,000
Mass Flow (Part.), Lb/Hr	50,000	500
Pressure, PSIA	13.75	13.75
Temperature, °F	310	310
Volume Flow, ACFM	1,990,000	1,990,000
Gas Composition (Vol.)		
CO_2, %	12.2	12.2
O_2, %	5.7	5.7
N_2, %	75.0	75.0
H_2O, %	6.9	6.9
SO2, PPM	1670	1670
Fly ash removed (Stream H)	49,500 Lb/Hr	
Bottom ash removed (Stream I)	12,500 Lb/Hr	

CASES 1 - 5	MADE	GILBERT ASSOCIATES, INC. ENGINEERS AND CONSULTANTS READING, PENNA.
FLOWDIAGRAM	CHK'D.	
FIGURE 4-2	SUP. SUPV.	
	ENG.	WORK ORDER / JOB DRAWING / REV.
	REV. CH. APP. DATE	

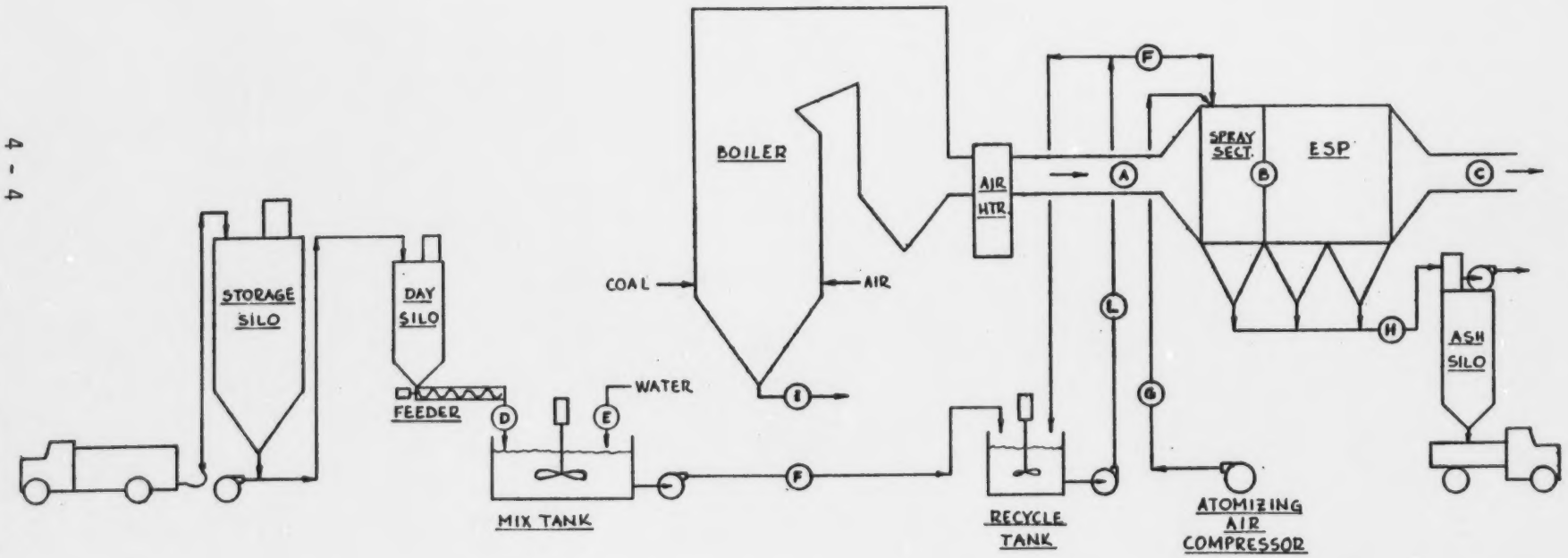

TABLE 4-2

MATERIAL BALANCE

CASES 1-4

STREAM

	A	B	C
Mass Flow (Gas), Lb/Hr	5,750,000	6,050,000	5,960,000
Mass Flow (Part.), Lb/Hr	50,000	94,200*	500*
Pressure, PSIA	13.75	13.75	13.75
Temperature, °F	310	162	162
Volume Flow, ACFM	1,990,000	1,680,000	1,660,000
Gas Composition (Vol.)			
CO_2, %	12.2	11.4	11.4
O_2, %	5.7	5.6	5.6
N_2, %	75.0	71.3	71.3
H_2O, %	6.9	11.5	11.5
SO_2, PPM	1670	783	783

STREAM

	D	E	F	G	H	I	L
Water, Lb/Hr	-	191,000	191,000	-	3,300	-	330,000
Water, GPM	-	382	-	-	-	-	-
Air, SCFM	-	-	-	16,700	-	-	-
$Ca(OH)_2$, Lb/Hr	31,300	-	31,300	-	-	-	54,000
Inerts, Lb/Hr	600	-	600	-	-	-	1,040
Total Solids, Lb/Hr	31,900	-	31,900	-	93,700*	12,500	-
Total Slurry, Lb/Hr	-	-	223,000	-	-	-	385,000
Total Slurry, GPM	-	-	405	-	-	-	700
Solids, %	-	-	14.3	-	-	-	14.3

*3.5% by weight water included

TABLE 4-3

MATERIAL BALANCE
CASE 5

STREAM

	A	B	C
Mass Flow (Gas), Lb/Hr	5,750,000	6,040,000	6,040,000
Mass Flow (Part.), Lb/Hr	50,000	99,300*	500*
Pressure, PSIA	13.75	13.75	13.75
Temperature, °F	310	172	172
Volume Flow, ACFM	1,990,000	1,700,000	1,700,000
Gas Composition (Vol.)			
CO_2, %	12.2	11.4	11.4
O_2, %	5.7	5.6	5.6
N_2, %	75.0	71.4	71.4
H_2O, %	6.9	11.2	11.2
SO_2, PPM	1670	786	786

STREAM

	D	E	F	G	H	I	L
Water, Lb/Hr	-	177,000	177,000	-	3,470	-	319,000
Water, GPM	-	354	-	-	-	-	-
Air, SCFM	-	-	-	16,000	-	-	-
$Ca(OH)_2$, Lb/Hr	36,100	-	36,100	-	-	-	64,900
Inerts, Lb/Hr	700	-	700	-	-	-	1,260
Total Solids, Lb/Hr	36,800	-	36,800	-	98,800*	12,500	66,200
Total Slurry, Lb/Hr	-	-	214,000	-	-	-	385,000
Total Slurry, GPM	-	-	389	-	-	-	700
Solids, %	-	-	17.2	-	-	-	-

*3.5% by weight water included

CASE 6		GILBERT ASSOCIATES, INC. ENGINEERS AND CONSULTANTS READING, PENNA.
FLOWDIAGRAM	MADE	
FIGURE 4-3	CHK'D.	
	DD. EP.	
	EP. DPW.	
	ENG.	WORK ORDER / DWG. DRAWING / REV.
	REV. CH. APP. DATE	

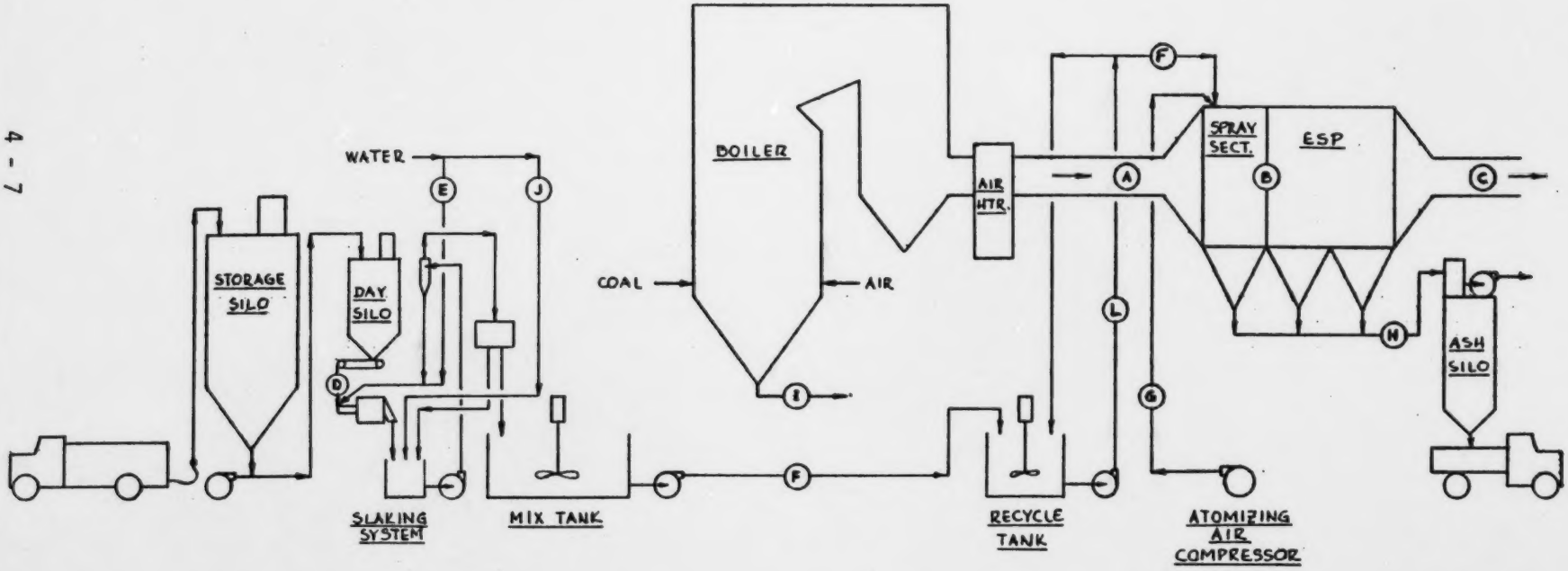

TABLE 4-4

MATERIAL BALANCE
CASE 6

	STREAM A	B	C
Mass Flow (Gas), Lb/Hr	5,750,000	6,070,000	6,070,000
Mass Flow (Part.), Lb/Hr	50,000	91,400*	500*
Pressure, PSIA	13.75	13.75	13.75
Temperature, °F	310	162	162
Volume Flow, ACFM	1,990,000	1,690,000	1,690,000
Gas Composition (Vol.)			
CO_2, %	12.2	11.4	11.4
O_2, %	5.7	5.6	5.6
N_2, %	75.0	71.1	71.1
H_2O, %	6.9	11.8	11.8
SO_2, PPM	1670	779	779

STREAM

	D	E	F	G	H	I	J	K	L
Water, Lb/Hr	-	89,200	202,000	-	3,300	-	121,000	81,600	342,000
Water, GPM	-	178	-	-	-	-	242	-	-
Air, SCFM	-	-	-	17,500	-	-	-	-	-
CaO, Lb/Hr	23,700	-	-	-	-	-	-	-	-
Inerts, Lb/Hr	2,100	-	1,050	-	-	-	-	1,050	1,800
$Ca(OH)_2$, Lb/Hr	-	-	31,300	-	-	-	-	31,300	53,000
Total Solids, Lb/Hr	25,800	-	32,400	-	94,200*	12,500	-	32,400	54,000
Total Slurry, Lb/Hr	-	-	234,000	-	-	-	-	114,000	396,000
Total Slurry, GPM	-	-	425	-	-	-	-	-	720
Solids, %	-	-	13.8	-	-	-	-	28.4	-

*3.5% by weight water included

In each case, raw reagent is unloaded to storage silos, forwarded to a day silo, slurried either by mixing with water (hydrated lime) or by slaking (quicklime), and pumped to a slurry holding tank from which a recycle pipe loop provides a bleed stream for the process. After injection, the dry solids product is removed in the precipitator and sent to a disposal silo for trucking to a landfill.

4.2 Equipment Description - Reagent Preparation and Delivery

The equipment which comprises the E-SOX system may be categorized into several subsystems:

1. Reagent Unloading and Storage, including truck unloading facilities, storage silos, and lime conveying system.

2. Slurry Preparation, including day silos, hydrated lime slurrying or quicklime slaking, and milk of lime storage and forwarding systems.

3. Reagent Recycle and Feed, including recycle tank, recycle pumps, and spray system.

4. Atomizing Air System, including compressors and distribution system.

5. Electrostatic Precipitator.

6. Solid Waste Handling, including precipitator ash removal system and storage silo.

4.2.1 Equipment Requirements

The same process design is used for Cases 1 through 4. Therefore, there is no essential difference in equipment between these cases except for the precipitator modifications in each case. Also,

because Case 4 assumes an additional precipitator field, the extra row of hoppers requires the solids removal system to be slightly different from the other cases. In Case 5, the higher calcium-to-sulfur ratio and higher approach temperature require some equipment to be slightly larger because of the greater lime usage. Case 6, with pebble lime, has fewer storage silos because of the greater density of this reagent with respect to the lime hydrate. Also, the slaking system results in different equipment for this subsystem.

4.2.2 Equipment Arrangement

As with any power plant, equipment layout is site specific. For retrofits, it is especially critical. As in the LIMB study, this study assumes adequate land area is available to permit a workable arrangement for the equipment. The reagent unloading, storage, and slurry preparation areas are considered to be remote from the boiler house because it is not realistic to assume space is available close by for equipment of this size. The area should be accessible from local roads since truck deliveries will be frequent. This area is assumed to be about 1300 feet from the reagent recycle and feed system. A building is provided to house transfer blowers and controls.

The reagent feed system, on the other hand, should be located as close as possible to the precipitator to keep pipe runs short and therefore facilitate draining and flushing of the system upon shutdown. The air compressors can be anywhere convenient, but should be reasonably close by to minimize problems with condensation and freezing in cold weather. This study assumes their siting is adjacent to the reagent feed system, in a new building. A new fly ash silo, required by the increased dry solids removed in the ESP, is located about 500 feet from the precipitator.

4.2.3 Lime Unloading and Storage

Raw lime, either hydrated or in pebble form, is received in pneumatically unloading tank trucks. These trucks have self-contained blowers, capable of unloading a 20-ton truck in about an hour. The unloading rate is a problem for a boiler of the size considered in this study, since the material cannot be unloaded fast enough from a single truck to keep up with the use rate if unloading is limited to a single shift. Such a schedule would be desirable for an actual operating plant.

There are at least four alternative solutions to this problem: (1) Extend unloading time; (2) Receive lime in larger bulk loads by either dump truck or rail, which would permit more rapid unloading; (3) Use specially constructed pneumatic trucks that would permit unloading up to about 50 tons per hour using stationary blowers at the lime silos; or (4) Unload more than one 20-ton truck at a time. For purposes of this study, recognizing that lime delivery is extremely site specific, the fourth alternative was chosen. Thus, provision is made to unload three trucks simultaneously.

Reagent is unloaded into large storage silos, closed to protect the lime from the weather. Roof-mounted dust collectors are provided. Silo height is limited by the ability of the truck unloaders to discharge reagent to the top, and silo diameter by consideration for flow out of the silo. Thus, for 30 days storage, more than one silo is required. The number of silos depends on the lime density. Six 2100-ton silos are used for hydrated lime and two 4700-ton silos for pebble lime.

From the storage silos, a pneumatic system is provided to forward the lime to a day silo which is sized to provide surge capacity in the system. 24-hours storage is provided. This silo is fitted with two outlet hoppers, each of which discharges to a feeder. A roof-mounted dust collector is provided to vent the silo.

4.2.4 Lime Slurry Preparation

Each day silo hopper outlet discharges to its own feeder. For Cases 1 through 5 (hydrated lime), these feeders are of the screw type and regulate flow of lime directly to a mix tank. Here, water is added in amounts designed to obtain the slurry strength required for cooling the flue gas to the desired approach temperature and to achieve the required Ca/S ratio. The slurry strength is shown in Tables 4-2, 4-3, and 4-4.

Case 6 differs since the reagent used is pebble lime. Because of the quantities used, a ball mill slaker system is the type considered for this study. Either of two weigh belt feeders measures lime from the day silo. Lime is fed through screw feeders to a ball mill, where water is mixed to produce the slurry. The product empties into a sump, dilution water is added, and the slurry is then pumped to a hydrocyclone. The hydrocyclone separates the coarse, unslaked lime which is returned to the ball mill; the slaked lime slurry goes to the mix tank or returns to the mill sump depending on process requirements.

The mix tank has a working capacity of about one hour's operation at full load. An agitator keeps the solids in suspension. Because the slurry preparation equipment is located adjacent to the lime storage area and is some distance from the boiler house, two parallel pipe lines, one of which is a spare, are provided to transport the slurry to a recycle tank near the precipitator. This minimizes the probability of limiting load in the event of one line plugging.

4.2.5 Reagent Recycling and Feed

The prime reason for the reagent recycling system is to maintain solids suspension in the piping during load swings. To accomplish this, a small tank (Recycle Tank) with about 10 minutes residence time is located as close as possible to the precipitator. One of

two parallel pumps (the second is a spare) circulates slurry through a pipe loop leading to the precipitator's roof and returning to the tank. Feed is then bled from this loop through short runs of pipe to the injection piping. By this means, low line velocities are limited only to the short runs.

The spray nozzles were based on equipment made by Babcock & Wilcox (MK-4 I-Jet nozzle). Atomization is by compressed air at 100 psig. Slurry pressure at full load is 85 psig, giving a flow of about 4.17 GPM per nozzle. Estimated droplet diameter is 30μm (Sauter mean diameter). A relatively flat size distribution is desirable since too large droplets may not have sufficient residence time to dry completely while too small droplets evaporate too rapidly and limit SO_2 removal.

In order to assess costs, it is assumed that reagent for the process is distributed, by a manifold above the precipitator roof, to several vertical feed pipes that hang into the first field cavity and to which the spray nozzles are attached. For the precipitators assumed, one hundred nozzles are required. Clamped loosely to each vertical feed pipe is an air feed pipe connected by flexible hoses to the spray nozzles. Both feed pipes mount to the precipitator through a flanged connection in the roof. Thus, both pipes are removed in a package for nozzle maintenance, yet each can expand and contract independently.

4.2.6 Atomizing Air

Atomizing air is required at about 100 psig pressure in quantities of about 0.35 lb air per lb. slurry at full load conditions. To supply this air, two three-stage centrifugal compressors, each delivering about 9000 SCFM, are required, operating in parallel. These are located in a compressor house to provide weather protection as well as noise containment. They are motor driven. Intercoolers are used between stages. Because of site-specific water costs, no water cooler is included herein.

4.3 Equipment Description - ESP Modifications

The study evaluated two different sized electrostatic precipitators. The larger precipitator is considered to be fairly representative of units installed in the early 1970's. The baseline SCA for this unit is 218 ft^2/kacfm; each of two ESP's is about 92 ft wide and 35 ft long. The second ESP has a baseline SCA of 150, and is of interest to establish the lower limits of precipitator SCA to which E-SOX may be applicable. Again, two precipitators are used; dimensions are approximately 105 ft wide by 25 ft long.

The precharger follows the general design described in Reference 6. However, because the slurry spray has already cooled the flue gas, the precharger is uncooled.

The approach to establish the final required ESP modifications was to use the Southern Research Institute ESP mathematical model to assess ESP performance based on E-SOX process conditions. A discussion of this approach is presented below.

4.3.1 ESP Retrofit Design Parameters

Two major issues were considered at some length during the mathematical modeling of ESP retrofit configurations for use with the E-SOX process.

a) The mathematical modeling tool (ESP MODEL) is unable to perform a reliable estimate of rapping reentrainment emissions from an outlet ESP field of unusual geometry, such as a short-field after-collector.

b) The American electric utility industry is reluctant to adopt unusual ESP retrofit configurations, such as water-flushed electrodes or mechanically moving electrodes.

Considerations of these two issues led to some changes from the ESP retrofit configurations that were originally proposed. The final set of assumptions about ESP retrofit work is summarized here.

All Cases. In addition to removing the electrodes from Field 1 and converting this space into a lime slurry spray chamber, the gas flow control devices are rebuilt as necessary to make the gas velocity distribution and gas sneakage consistent with current industry practice. In the ESP MODEL, S represents the fractional gas sneakage past each baffled section. Each separately energized electrical field is assumed to be baffled, with ideal re-mixing of the gas stream. Sigma represents the standard deviation of a matrix of gas velocity measurements over the face of the ESP, divided by the average value. Values of 0.10 and 0.25 for S and sigma, respectively, are assumed for the baseline ESP. After modification, gas flow control devices are assumed to yield values of 0.05 and 0.15 for S and sigma, respectively, which are representative of modern ESP design and construction. The ESP is reconfigured as necessary to achieve particulate emissions below the limit of 0.1 $lb/10^6$ Btu.

Cases 1, 2, 5, and 6. These four cases begin with an existing (baseline without E-SOX) three-field weighted-wire ESP with an SCA of 218 $ft^2/1000$ acfm, collection efficiency of 99.38 percent, and particulate emissions of 0.060 $lb/10^6$ Btu.

Cases 3 and 4. These two cases begin with an existing (baseline without E-SOX) three-field weighted-wire ESP with an SCA of 150 $ft^2/1000$ acfm, collection efficiency of 98.6 percent, and particulate emissions of 0.136 $lb/10^6$ Btu. In both baseline ESP configurations, the average gas velocity is about 5.5 ft/sec.

Cases 1, 5, and 6. These three cases differ only in regard to variations in process parameters which have little effect on the ESP configuration and performance. In all three cases, a precharger is placed in front of Field 2 and large-diameter

discharge electrodes are installed in Fields 2 and 3. Based on the ESP model, no increase in plate area is required. In a rebuild with large-diameter discharge electrodes, it is possible that the plate spacing would be increased to 10 or 12 inches, and some sort of rigid discharge electrode structure would be used. However, since this is a site specific determination, for these ESP performance estimates the plate spacing is kept at 9 inches for all cases.

Cases 2 and 4. The retrofit work consists only of enlarging the plate area in the direction of gas flow. No change in the electrode design is required. In Case 2, the plate length in Fields 2 and 3 is extended from 9 feet to 10.5 feet. There is assumed to be space available in the ESP to lengthen the plates. In Case 4, a 3-foot field is added to the two 6-foot fields, giving one additional baffled section of gas flow. Because of the problems with estimating emissions due to rapping reentrainment, the additional short field is modeled at the front of the ESP rather than at the back.

Case 3. In addition to installing a precharger and large-diameter discharge electrodes, the plate dimensions in Fields 2 and 3 are increased from 30 x 6 feet to 33 x 7.5 feet. The extra height is obtained by raising the precipitator roof, the length merely by using longer plates as in Case 2. Case 3 is the only case which combines retrofit electrodes with plate area enlargement.

4.3.2 ESP MODEL Input Data

Particle Size Distribution

A particle size distribution was calculated for the process variables (gas flow, fly ash mass, sorbent mass) of Case 1. Dried sorbent particles are mostly larger than 2 μm, as shown below, and their exact size distribution has less effect on ESP collection

efficiency than other operating variables. Therefore, the same particle size distribution was used for all cases.

The first step of the calculation was to determine a size distribution for the fly ash particles. Under EPRI RP629-5 (Reference 7) seventeen eastern bituminous coal fly ashes were classified as to particle size distribution. The average mass median diameter of these fly ashes was 16.3 μm, with a sigma of 3.4. A cumulative percent mass distribution was determined for this baseline fly ash using eight evenly spaced particle size bands per logarithmic decade. From this distribution, the dM/dlogD was calculated and plotted at the geometric mean diameters using a total mass loading of 3.47 gr/acf at 162°F, as shown in Table 4-5. The next step began with a droplet cumulative percent mass distribution measured by B&W for the MK-4 I-Jet nozzle. This distribution was plotted on log-probability graph paper and smoothed. The calculated Sauter mean diameter for the smoothed distribution was 26 μm. The dried particle size distribution was calculated and plotted. The cumulative percent mass values were used to calculate dM/dlogD for the dried particles, which was plotted versus the geometric mean diameters using a total mass loading of 3.07 gr/acf, as given in Table 4-6. The third step was to sum the two curves and obtain a graph of dM/dlogD versus geometric mean diameter for the composite of fly ash and dried sorbent particles. This curve was plotted with dM/dlogD versus geometric mean diameter. These values were converted back to cumulative percent mass, using a total particulate mass loading of 6.54 gr/acf, as shown in Table 4-7.

Three figures were generated from these calculations. Figure 4-4 is a graph of cumulative percent mass versus particle diameter for the fly ash, sorbent, and the mathematically generated composite. Figure 4-5 is a graph of the droplet size data for the MK-4 I-Jet nozzle with a smoothed curve superimposed on the measured data. The dried particle curve shows a shift to the left (by a factor of 0.53) and represents the data which were used in generating the

TABLE 4-5
FLY ASH PARTICLE SIZE DISTRIBUTION
(Total Mass Loading = 3.47 gr/acf)

Diameter μm	Cumulative % Mass	ΔM/ΔlogD gr/acf	$\sqrt{D_1D_2}$ μm
.154	0.0		
		0.006	0.178
.205	0.020		
		0.008	0.237
.274	0.049		
		0.017	0.316
.365	0.110		
		0.033	0.422
.487	0.230		
		0.061	0.562
.649	0.450		
		0.111	0.750
.866	0.850		
		0.208	0.998
1.15	1.60		
		0.333	1.33
1.54	2.80		
		0.527	1.78
2.05	4.70		
		0.778	2.37
2.74	7.50		
		0.972	3.16
3.65	11.0		
		1.39	4.22
4.87	16.0		
		1.72	5.62
6.49	22.2		
		2.17	7.50
8.66	30.0		
		2.36	9.98
11.5	38.5		
		2.64	13.3
15.4	48.0		
		2.50	17.8
20.5	57.0		
		2.50	23.7
27.4	66.0		
		2.28	31.6
36.5	74.2		
		1.89	42.2
48.7	81.0		
		1.61	56.2
64.9	86.8		
		1.17	75.0
86.6	91.0		
		0.944	99.8
115.	94.4		
		1.55	133.0
154.	100.0		

TABLE 4-6

SORBENT PARTICLE SIZE DISTRIBUTION

(Total Mass Loading = 3.07 gr/acf)

Droplet Diameter μm	Dry Diameter μm	Cumulative % Mass	ΔM/ΔlogD gr/acf	$\sqrt{D_1 D_2}$ μm
1.54	0.816	0.0	0.005	0.943
2.05	1.09	0.020	0.009	1.26
2.74	1.45	0.058	0.023	1.67
3.65	1.93	0.150	0.056	2.23
4.87	2.58	0.380	0.128	2.98
6.49	3.44	0.900	0.270	3.97
8.66	4.59	2.0	0.614	5.29
11.5	6.10	4.50	1.23	7.06
15.4	8.16	9.50	2.09	9.43
20.5	10.9	18.0	4.18	12.6
27.4	14.5	35.0	6.63	16.7
36.5	19.3	62.0	5.65	22.3
48.7	25.8	85.0	2.85	29.8
64.9	34.4	96.6	0.749	39.7
86.6	45.9	99.65	0.086	52.9
115.	61.0	100.0		

Displacement Density of Solid, RHO_s = 1.9 g/cm^3

Particle Density, RHO_p = 1.0 g/cm^3

Mass Ratio Solid/Water = 0.164

Diameter Ratio Particle/Droplet = 0.53

TABLE 4-7
COMPOSITE PARTICLE SIZE DISTRIBUTION
(Total Mass Loading = 6.54 gr/acf)

Diameter μm	Cumulative % Mass	ΔM/ΔlogD gr/acf	$\sqrt{D_1D_2}$ μm
.154	0.0	0.006	0.178
.205	0.011	0.008	0.237
.274	0.026	0.017	0.316
.365	0.058	0.033	0.422
.487	0.121	0.061	0.562
.649	0.238	0.114	0.750
.866	0.456	0.214	0.998
1.15	0.865	0.346	1.33
1.54	1.53	0.556	1.78
2.05	2.59	0.848	2.37
2.74	4.21	1.13	3.16
3.65	6.37	1.73	4.22
4.87	9.68	2.40	5.62
6.49	14.3	3.47	7.50
8.66	20.9	4.66	9.98
11.5	29.8	7.74	13.3
15.4	43.6	9.10	17.8
20.5	61.0	7.70	23.7
27.4	75.7	4.53	31.6
36.5	84.4	2.49	42.2
48.7	89.2	1.67	56.2
64.9	92.4	1.17	75.0
86.6	94.6	0.944	99.8
115.	96.4	1.88	133.0
154.	100.0		

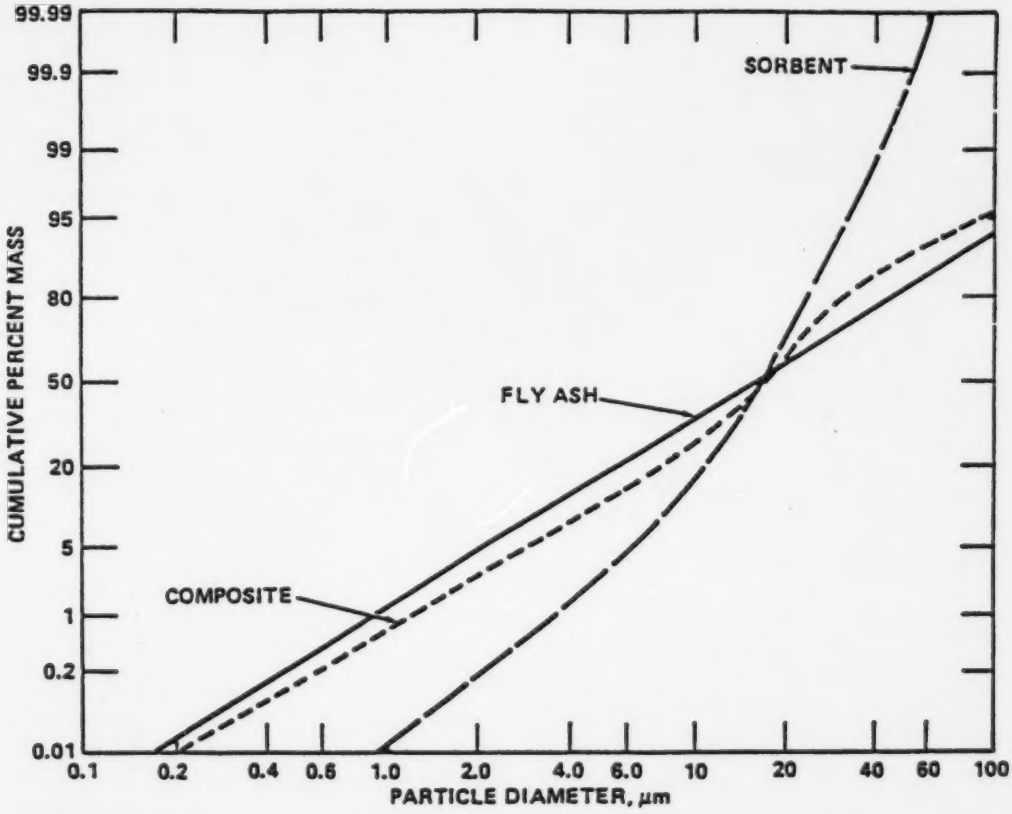

Figure 4-4 Particle Size Distributions in Cumulative Percent Mass.

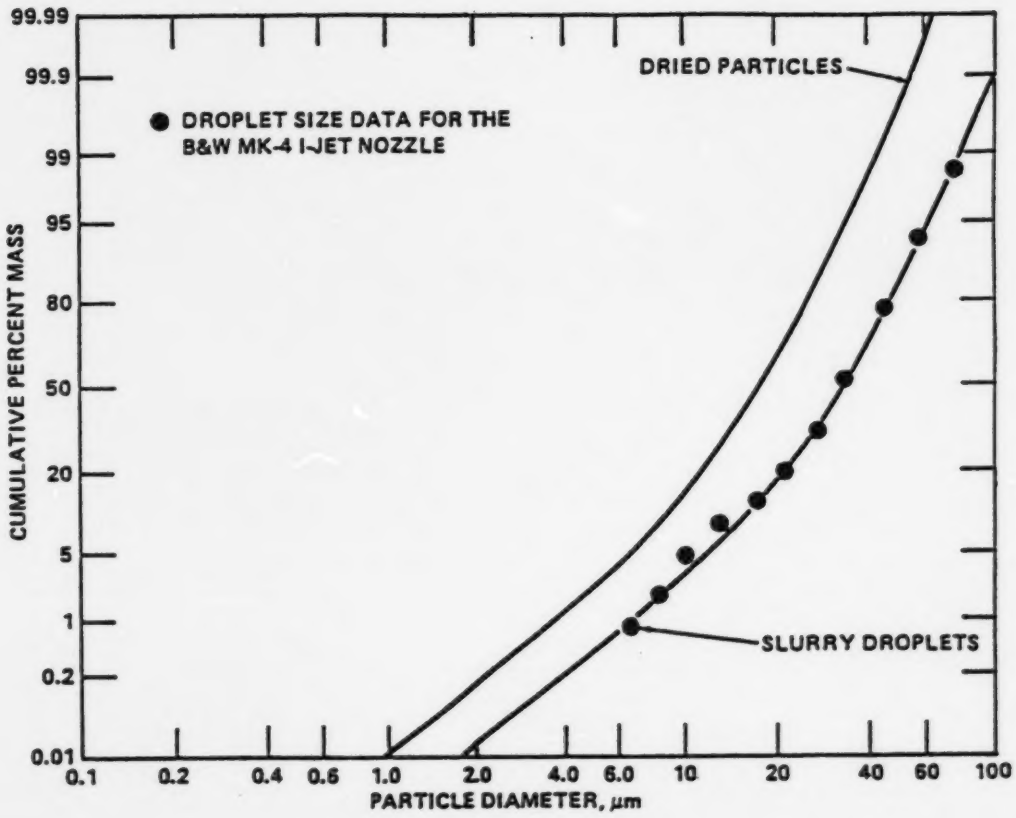

Figure 4-5 Particle Size Distributions in Cumulative Percent Mass for Slurry Droplets and Dried Sorbent Particles.

composite particle size distribution. Figure 4-6 is a graph of dM/dlogD versus geometric mean diameter for the fly ash, sorbent, and composite.

Bulk Dust Resistivity

In all cases, before and after an E-SOX retrofit, the dust resistivity is assumed to be low enough that it does not constrain the electrification of the ESP. For the baseline operation with fly ash from 2.5% sulfur coal, about 7 ppm of free SO_3 (actually H_2SO_4) is expected to be in the flue gas entering the ESP, and the fly ash resistivity is expected to be about 5×10^9 ohm-cm at 310°F. The baseline ESP electrical operating points (Tables 4-8 and 4-9) correspond to fly ash resistivity of about 10^{10} ohm-cm from the SRI data base of measurements performed on utility fly ash precipitators. The computed baseline ESP performance is reasonable for a small ESP that is in good electrical and mechanical operating condition and that makes effective use of high electrical power consumption.

After an E-SOX retrofit, the dust resistivity is expected to remain low as a result of the reduced gas temperature and increased flue gas moisture content.

Precharger Design and Performance Data

A cooled-pipe precharger has been developed by Denver Research Institute. One set of tests of the precharger at Valmont Station (Colorado Public Service Company) produced Q/M data (particle charge-to-mass ratio) in the particle diameter range 1.1 μm to 2.6 μm, obtained with an electrically isolated impactor stage. The

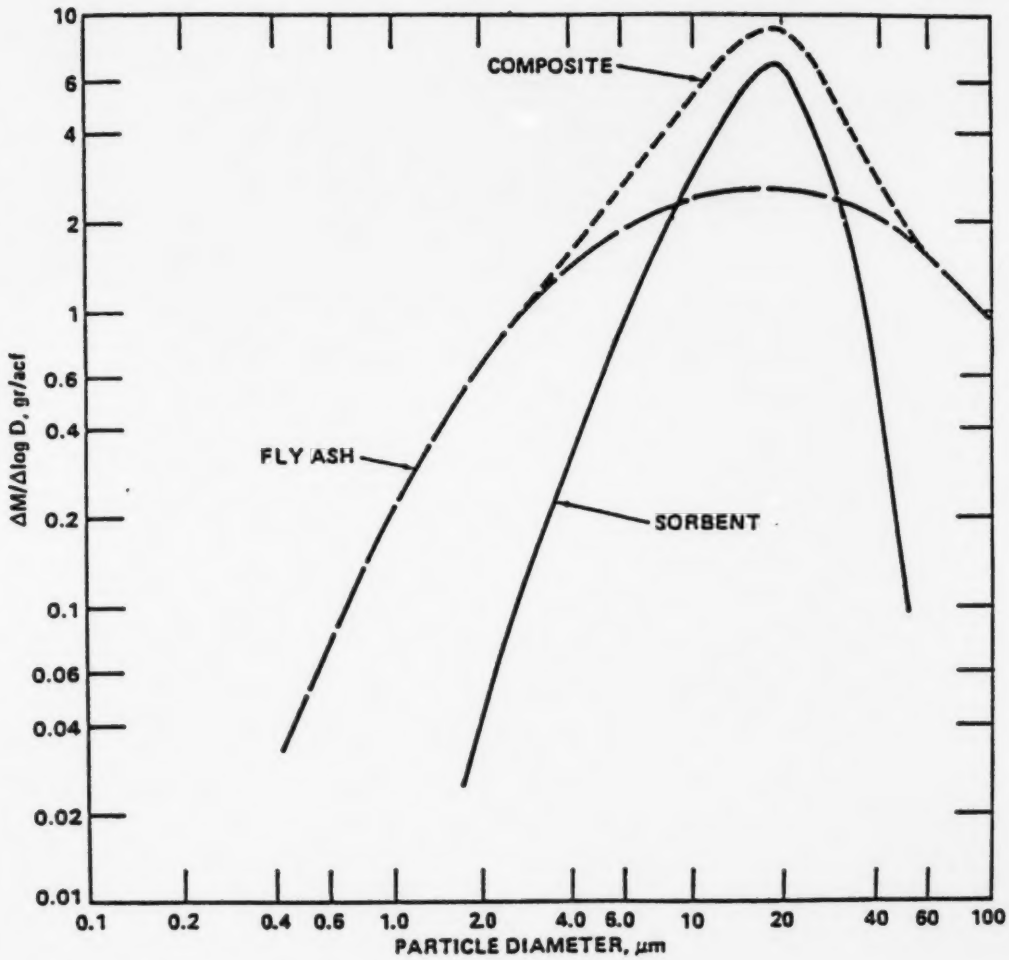

Figure 4-6 Particle Size Distributions Used to Form the Composite of Fly Ash and Dried Sorbent Particles.

TABLE 4-8

SUMMARY OF ESP DESIGN PARAMETERS AND COMPUTED PERFORMANCE

(Baseline SCA 218 ft^2/1000 acfm)

	Baseline	Case 0 E-SOX No fix	Case 1 Two Stage	Case 2 Plate Area	Case 5 Ca/S T	Case 6 Slaked Lime
Gas Flow Parameters						
Gas Passages	61					
Face Area, ft^2	1059.75					
Gas Flow, 1000 acfm	497.5	420.0	420.0	420.0	425.0	422.5
Gas Velocity, ft/s	5.49	4.64	4.64	4.64	4.69	4.66
Treatment Time, s	4.92	3.88	3.88	4.52	3.84	3.86
SCA, ft^2/1000 acfm	218	173	173	201	171	172
Aspect Ratio	0.82	0.55	0.55	0.64	0.55	0.55
Temperature, °F	310	162	162	162	172	162
Viscosity, 10^{-5} kg/m/s	2.27	1.87	1.87	1.87	1.89	1.87
Ratio acf/dscf	1.675	1.423	1.423	1.423	1.441	1.428
Precharger Field						
Plate Height, ft			33		33	33
Plate Length, ft			0.2		0.2	0.2
Plate Area, ft^2			805		805	805
Operating Voltage, kV			45		45	45
Current Density, $\mu A/ft^2$			240		240	240
First Collector Field						
Plate Height, ft	33	33	33	33	33	33
Plate Length, ft	9	9	9	10.5	9	9
Plate Area, ft^2	36234	36234	36234	42273	36234	36234
Operating Voltage, kV	44	44	50	44	50	50
Current Density, $\mu A/ft^2$	25	25	9	25	9	9

TABLE 4-8 (Continued)

	Baseline	Case 0 E-SOX No fix	Case 1 Two Stage	Case 2 Plate Area	Case 5 Ca/S T	Case 6 Slaked Lime
Second Collector Field						
Plate Height, ft	33	33	33	33	33	33
Plate Length, ft	9	9	9	10.5	9	9
Plate Area, ft^2	36234	36234	36234	42273	36234	36234
Operating Voltage, kV	43	43	50	43	50	50
Current Density, $\mu A/ft^2$	39	39	9	39	9	9
Third Collector Field						
Plate Height, ft	33					
Plate Length, ft	9					
Plate Area, ft^2	36234					
Operating Voltage, kV	41					
Current Density, $\mu A/ft^2$	36					
Particulate Mass Loading						
Inlet, gr/acf	2.93	6.54	6.54	6.54	6.81	6.31
Inlet, $lb/10^6$ Btu	9.74	18.73	18.73	18.73	19.73	18.16
Computer Mass Emissions						
($S=0.10$, $\sigma=0.25$)						
Outlet, $lb/10^6$ Btu	.06	.26				
Collection Efficiency	99.38	98.6				
Computer Mass Emissions						
($S=0.05$, $\sigma=0.15$)						
Outlet, $lb/10^6$ Btu			.08	.08	.08	.08
Collection Efficiency			99.59	99.56	99.57	99.58

TABLE 4-9

SUMMARY OF ESP DESIGN PARAMETERS AND COMPUTED PERFORMANCE

(Baseline SCA 150 ft^2/1000 acfm)

	Baseline	Case 0 E-SOX No fix	Case 0 Two Stage	Case 4 Plate Area	Case 3 Plate Area
Gas Flow Parameters					
Gas Passages	69				
Face Area, ft^2	1552.5				
Gas Flow, 1000 acfm	497.5	420.0	420.0	420.0	420.0
Gas Velocity, ft/s	5.34	4.51	4.51	4.51	4.10
Treatment Time, s	3.37	2.66	2.66	3.33	3.66
SCA, ft^2/1000 acfm	150	118	118	148	163
Aspect Ratio	0.60	0.40	0.40	0.50	0.45
Temperature, °F	310	162	162	162	162
Viscosity, 10^{-5} kg/m/s	2.27	1.87	1.87	1.87	1.87
Ratio acf/dscf	1.675	1.423	1.423	1.423	1.423
Precharger Field					
Plate Height, ft			30		33
Plate Length, ft			0.2		0.2
Plate Area, ft^2			1224		1346
Operating Voltage, kV			45		45
Current Density, $\mu A/ft^2$			240		240
First Collector Field					
Plate Height, ft	30	30	30	30	33
Plate Length, ft	6	6	6	3*	7.5
Plate Area, ft^2	24840	24840	24840	12420	34155
Operating Voltage, kV	44	44	50	44	50
Current Density, $\mu A/ft^2$	25	25	9	25	9

* Short field modelled as first field because of computer program limitations. Costs are based on two 6-ft. fields followed by 3-ft. field.

TABLE 4-9 (Continued)

	Baseline	Case 0 E-SOX No fix	Case 0 Two Stage	Case 4 Plate Area	Case 3 Plate Area
Second Collector Field					
Plate Height, ft	30	30	30	30	33
Plate Length, ft	6	6	6	6	7.5
Plate Area, ft^2	24840	24840	24840	24840	34155
Operating Voltage, kV	43	43	50	43	50
Current Density, $\mu A/ft^2$	39	39	9	39	9
Third Collector Field					
Plate Height, ft	30			30	
Plate Length, ft	6			6	
Plate Area, ft^2	24840			24840	
Operating Voltage, kV	41			41	
Current Density, $\mu A/ft^2$	36			36	
Particulate Mass Loading					
Inlet, gr/acf	2.93	6.54	6.54	6.54	6.54
Inlet, $lb/10^6$ Btu	9.74	18.73	18.73	18.73	18.73
Computer Mass Emissions					
($S=0.10$, $\sigma=0.25$)					
Outlet, $lb/10^6$ Btu	.14	.45			
Collection Efficiency	98.6	97.6			
Computer Mass Emissions					
($S=0.05$, $\sigma=0.05$)					
Outlet, $lb/10^6$ Btu			.14	.07	.08
Collection Efficiency			99.26	99.62	99.57

tests were performed with high-resistivity fly ash, at a flue gas temperature of 300°F. The mean gas velocity was 4.6 ft/s, but the velocity was 36% higher between the pipes. Mathematical modeling of the precharger has been tested only against those Q/M data. There are no reliable experimental data about particle collection in the precharger, with or without reentrainment. All estimates of collection efficiency have been obtained by back calculation from measurements of outlet mass loading downstream of collector sections.

In the tests at Valmont, the water-cooled pipes were 2.375-inch OD, on 9-inch centers. The closest wire-pipe spacing was 3.3 inches. There were 6 parallel gas passages. The pipes were 12 feet high, including a few inches past the upper and lower ends of the discharge wires. The total collecting surface area (using the projected pipe area) was 4100 in^2 (26,500 cm^2). The Q/M data were obtained during operation with 43.5 kV and 5 mA, giving a current density of about 189 nA/cm^2.

The particle charging calculation was tested by using an equivalent wire-plate geometry that can be treated by the ESP MODEL. The input data based on the Valmont tests and the calculated values of Q/M are summarized in Table 4-10. The results are reasonably consistent with both experimental and theoretical Q/M values from Valmont of about 14 μC/g, in the particle diameter range of 1.1 to 2.6 μm. The purpose of this calculation was to test the modeling of the precharger with an equivalent wire-plate geometry.

For the ESP performance computations, the equivalent wire-plate spacing is chosen to be 3.05 inches. For Cases 1, 2, 5, and 6, there are 90 gas passages through the precharger. For Cases 3

TABLE 4-10

INPUT DATA FOR THE ESP MODEL, USED TO SIMULATE A COOLED-PIPE PRECHARGER, AND COMPUTED VALUES OF PARTICLE CHARGE-TO-MASS RATIO

Plate Length	2.375 inch
Wire-Plate Spacing	3.3 inch
Inlet Mass Loading	0.4 gr/acf
Inlet Particle Size Distribution	mmd = 7.4 μm, σ = 2.7
Gas Velocity	6.25 ft/s
Voltage	43.5 kV
Current	5 mA
Current Density	189 nA/cm^2
Average E Field	5.2 kV/cm
E Field at Plate	4.5 kV/cm
Q/M	
1.0 μm	36 μC/g
1.5 μm	23 μC/g
2.2 μm	16 μC/g
3.0 μm	11 μC/g

and 4, there are 102 gas passages. The equivalent plate length is chosen to be 2.4 inches. Optimum electrical operating conditions in the cooled-pipe precharger at Valmont have been reported to be 45 kV and 260 nA/cm^2 (240 μA/ft^2). These numbers are used for the ESP performance computations, as shown in Tables 4-8 and 4-9.

Large-Diameter Discharge Electrodes

Large-diameter discharge electrodes are intended to increase the interelectrode electric field strength, while maintaining sufficient discharge current to clamp the collected fly ash deposit. A rod diameter of about 3/8 inch has been found to achieve this effect and to give an adequate range of working voltage between corona onset and spark limit. This section describes the basis of choosing electrical operating points to compute the ESP performance when the conventional corona wires are replaced by large-diameter discharge electrodes.

The 30,000 acfm pilot-scale precipitator at the Bull Run Steam Plant of TVA was tested with 10-inch plate spacing and with 3/8 inch rods installed throughout the box as high voltage discharge electrodes. The tests were performed with high-resistivity fly ash, 2 X 10^{12} to 4 X 10^{12} ohm-cm, at 325°F. The measured V-I curves are shown in Figure 4-7. Average plate current densities in the range of 5 to 7 μA/ft^2 were achieved before the electrodes went into continuous sparking, with the sparking frequency controlled by the current limit of the T-R set.

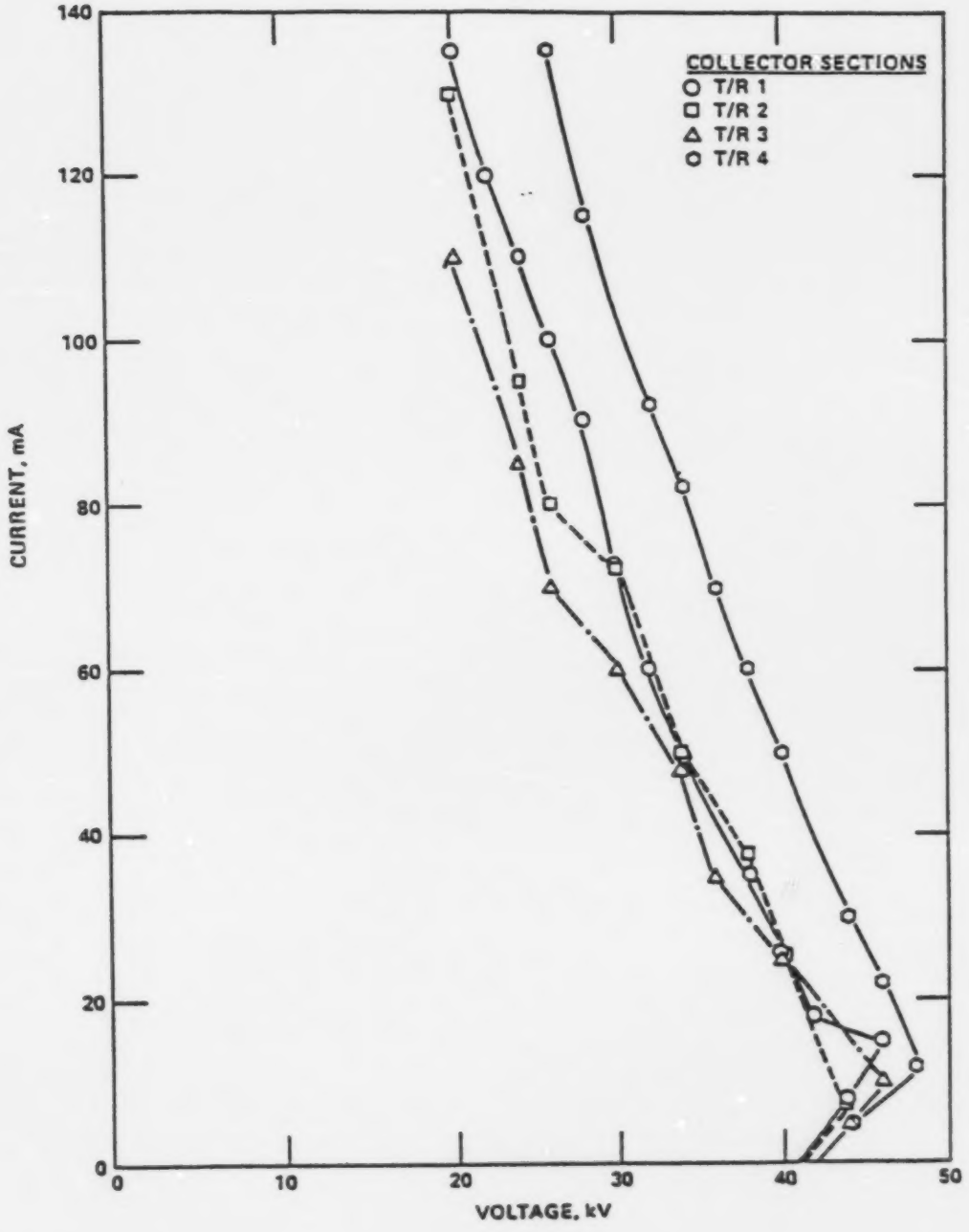

Figure 4-7 Voltage-Current Characteristics for 3/8-inch Rods in 10-inch Ducts, with High-Resistivity Fly Ash at 325°F.

There are no electrical operating data available for large-diameter electrodes with low-to-moderate-resistivity fly ash. Based on an optimistic extrapolation of the V-I curves in Figure 4-7, the electrical operating point with low-resistivity dust and 9-inch plate spacing is chosen to be 50 kV and 9 $\mu A/ft^2$, as shown in Tables 4-8 and 4-9.

4.3.3 ESP Performance

The design parameters for baseline and retrofit ESP configurations are given in Tables 4-8 and 4-9. The computed ESP collection efficiency and particulate mass emissions based on these parameters are tabulated for each case.

A comparison of Cases 1 and 2 shows that a modest increase in plate length will achieve the same ESP performance improvement as the installation of novel electrodes. With low-resistivity fly ash and reasonable plate area after an E-SOX retrofit (SCA of 173 $ft^2/1000$ acfm prior to ESP modifications) the precharger offers little performance advantage. It accomplishes quickly the dust particle charging that otherwise would be accomplished within 2 or 3 feet of travel along a conventional gas passage. The large-diameter discharge electrodes, on the other hand, offer a performance advantage due to the increased interelectrode electric field. In Cases 3 and 4, with a much lower plate area after an E-SOX retrofit (SCA of 118 $ft^2/1000$ acfm prior to ESP modifications) a substantial re-build of the ESP is required to limit particulate emissions to 0.1 $lb/10^6$ Btu.

4.4 Solids Disposal

Because additional particulate is removed by the precipitator when E-SOX is applied, the fly ash handling system must be upgraded. For this study, the rate of solids handling is almost doubled. Consequently, the existing system, assumed to be a dry vacuum system, is modified to serve one precipitator, and a new dry vacuum

system, including a new silo, is installed for the other precipitator. The new vacuum system is rated at 50 TPH. It was assumed that no size reduction equipment (such as a delumper) would be required on the ESP hoppers for the existing or new solids handling system. The new silo has three days storage capacity.

4.5 Electrical Distribution System

Electrical gear is required to serve the new equipment. It was assumed that power can be obtained from an existing 4 kV bus. Included in the design are switchgear, motor control centers, cable and conduit, lighting, instrumentation and controls. Most of the power used is for the atomizing air compressors (about 3000 kW).

5.0 ECONOMIC SUMMARY

5.1 Capital Cost Estimates

The capital cost estimates for the six design cases reflect the present day plant investments required to retrofit the E-SOX process to an existing coal-fired power plant. The estimates were uniformly prepared for consistency and are based on cost information obtained from equipment vendors and from in-house information and knowledge of current power plant costs. All estimates are at the January, 1987 price level for labor, materials, equipment and services.

The cost estimates have been prepared from sketches, conceptual arrangements and preliminary information and, hence, are conceptual estimates. The work included in the estimates includes the facilities and equipment required to unload, store, prepare and inject lime slurry into a modified ESP. Also included are ESP modifications, ash system modifications, ash handling piping and controls and balance-of-plant electrical and civil modifications.

It was assumed that there are no major site problems or interferences which would lead to extraordinarily high retrofit costs. No cost allowance has been included for acquiring additional land.

Major equipment prices are based on vendor furnished cost information. Other equipment prices are allowances based on historical cost data for equipment in similar applications. Bulk commodities such as concrete, structural steel, piping, conduit, cable tray and cable have been priced using current in-house pricing information. Base case costs have been factored in many instances to arrive at costs for the other cases.

Labor costs are based on work being done by a union contractor working a 5 day, 40 hour work week. The labor pricing was

calculated based on composite labor rates which include wages, fringe benefits, payroll taxes, insurances, temporary facilities, field office overhead, construction equipment, small tools, expendable supplies, home office, overhead and profit.

Engineering, construction management and owner's engineering, supervision and administrative costs have been included at 20% of the direct construction costs.

Contingency has been allowed at 20% of direct and indirect costs to cover requirements which are undefined in the conceptual design.

Escalation of present day costs to a future construction schedule is not included. All costs are at the January, 1987 price level. Interest during construction also is not included. However, for a construction period of one year or less, which would be likely in this case, interest during construction is not usually included. In addition, the following items have not been included in the estimate: premium pay for contractor's forces, sales tax, escalation, project financing costs, startup costs and inventory capital.

A summary of the capital costs is provided in Table 5-1. To provide for equitable comparisons, the power production of the unit is not derated by the energy demanded by the E-SOX system. Energy demand is treated as an operational cost. The cost estimate details are provided in the Appendix.

TABLE 5-1
E-SOX PROCESS RETROFIT CAPITAL COST SUMMARY ($10^3$$)

(January 1987 Dollars)

	Case No.					
	1	2	3	4	5	6
Civil/Structural Work	4,268	4,268	4,268	4,268	4,268	1,833
Mechanical Work	8,224	11,389	10,739	8,438	8,224	8,452
Electrical Work	783	783	783	783	783	776
Subtotal-Present Day Construction Cost	13,275	16,440	15,790	13,489	13,275	11,061
Engineering, Construction Management, and Owner's Cost	2,655	3,288	3,158	2,698	2,655	2,212
Subtotal	15,930	19,728	18,948	16,187	15,930	13,273
Contingency	3,186	3,946	3,790	3,237	3,186	2,655
Total Plant Investment	19,116	23,674	22,738	19,424	19,116	15,928
$/kW	38	47	45	39	38	32

An analysis of the breakdown of costs indicates that the cost for increasing the size of the existing precipitator by lengthening existing fields or raising the roof in Cases 2 and 3, respectively, is much more than the cost of the precharger and large diameter electrode modifications. Even adding a field (Case 4) does not as significantly raise the cost as the taller plates.

For all other equipment, the only significant difference in capital cost is for Case 6 in which the reagent is pebble lime. Even though a slaking system is required here, the much higher density of the bulk lime permits smaller equipment in the receiving, storage, and preparation areas. The overall effect is to lower capital cost.

The capital costs for E-SOX compare very favorably with other retrofit SO_2 removal technologies. This is attributed to the maximum use of existing equipment (no new ductwork or ID fans) and minimal new equipment requirements.

5.2 Operation and Maintenance Costs

Incremental first year operation and maintenance costs for the E-SOX cases consist of the following components:

1. Lime use
2. Power consumption
3. Solids disposal
4. Water consumption
5. Operating labor
6. Maintenance labor and materials

First year cost calculations for items 2, 3, and 5 are as used in the LIMB study (Reference 1) escalated to January 1987 at 4 percent per year. The factors used are:

1. Cost of lime (hydrate or pebble): $47.00 per ton

2. Replacement energy cost: $287.00 per kW-year

3. Solids disposal cost: $6.75 per ton

4. Cost of water: $0.30 per 1000 gal.

5. Operating labor: $21.38 per hour

6. Maintenance labor and materials: 4 percent of the direct construction costs

Table 5-2 summarizes the O&M cost components and the total first year operating costs for the six design cases. The first year O&M costs for an E-SOX retrofit range from about 6.2 to 7.6 million dollars, or about 2.2 to 2.7 mills per kilowatt-hour.

Unit consumptions were based on a 65 percent capacity factor (5700 operating hours per year). The solids disposal component is an incremental charge for the additional calcium solids produced from the SO_2 removal.

The power consumption component reflects a credit in precipitator power usage for more efficient use of power and fewer active fields. The power used by the air compressors represents almost 90 percent of the total incremental power consumption.

TABLE 5-2

SUMMARY OF FIRST YEAR OPERATING AND MAINTENANCE COSTS

(January 1987 Dollars)

	Design Case					
	1	2	3	4	5	6
1. Lime consumption, kT	90.8	90.8	90.8	90.8	105	73.5
Cost of lime, k$	4,270	4,270	4,270	4,270	4,940	3,450
2. Power consumption, kW	2,740	2,970	2,900	3,040	2,630	3,000
Cost of power, k$	786	852	832	872	754	861
3. Solids disposal, kT	133	133	133	133	141	134
Cost of disposal, k$	898	898	898	898	952	905
4. Water consumption, MMgal	445	445	445	445	422	473
Cost of water, k$	134	134	134	134	127	142
5. Operating labor, kMH	8.8	8.8	8.8	8.8	8.8	13.1
Operating cost, k$	187	187	187	187	187	281
6. Maintenance L&M, %	4	4	4	4	4	4
Cost of maintenance, k$	515	642	616	524	515	427
Total First Year O&M Cost, k$	6,800	6,980	6,940	6,890	7,480	6,070
Mills per kW-hr	2.39	2.45	2.44	2.42	2.62	2.13

NOTE: Water consumption includes E-SO_x related plant water and compressor cooling water, as well as water for slurry and hydration.

The following components are excluded from the first year O&M cost of the E-SOX system:

1. Operation and maintenance of the existing fly ash removal system.

2. Outage penalties relating to availability/reliability of the E-SOX equipment.

Solids disposal costs were assumed to be an operational cost on the basis of $6.75 per ton. If a utility had to open or expand a landfill to accommodate the extra solid waste, an additional capital cost increment would be applicable.

The operating cost breakdown reflects the advantage of using pebble lime rather than lime hydrate. Because of the lower molecular weight of the quicklime, there is a savings in the number of tons per year required to obtain the same Ca/S ratio as with hydrated lime, and, since the delivered cost is virtually the same for each, the operating cost is also lower. This is so even though the slaking system adds to the electric power used as well as, in all probability, more manpower to operate it.

5.3 Annualized Costs

As a means to compare overall costs of the systems, Table 5-3 presents total costs on an annualized basis. For this comparison, a fixed charge rate of 18 percent is used.

TABLE 5-3

FIRST YEAR ANNUALIZED COSTS ($1000/YR)

(January 1987 Dollars)

	Case No.					
	1	2	3	4	5	6
Annualized Capital Cost	3,440	4,260	4,090	3,500	3,440	2,870
First Year O&M Cost	6,800	6,980	6,940	6,890	7,480	6,070
Total Annualized Cost	10,240	11,240	11,030	10,390	10,920	8,940
$/ton SO_2 removed	345	378	371	350	368	301

6.0 RESULTS AND CONCLUSIONS

This study is considered representative of the retrofit of an E-SOX system to the type of utility power generating unit selected, i.e, a 500 MW unit burning a medium sulfur eastern coal. The study includes all equipment required to accomplish the retrofit without the need for acquiring additional land area. The comparisons made show the relative magnitude of cost differentials for different sizes of precipitators as well as for two types of lime reagent and lime requirement. The comparisons made should be valid for a given situation, although the sensitivity to site location may have a significant impact on the magnitude of the costs. However, G/C considers the results presented herein are comparable to other "generic" SO_2 retrofit technology studies (such as LIMB).

It should be noted that the process design is based on rather limited laboratory scale experimental data. It is not likely that a retrofit of this type would be undertaken for a power plant of this size without first demonstrating the technology on an intermediate scale. For example, the assumption of 50% SO_2 removal at Ca/S = 1.3 and an approach temperature of 40°F implies that the calcium utilization is almost 40%. This assumption is consistent with data and models published in the literature, but some recent data have indicated much lower values of calcium utilization. An intermediate scale demonstration is required to show satisfactory SO_2 removal along with reliable equipment operation.

The mechanical equipment used as a basis for these designs is predominantly commercial. Lime receiving and storage and slurry preparation are state-of-the-art for many existing scrubbers, both wet and dry. On the other hand, the two fluid nozzle arrangement requires some developmental work. Also, some of the precipitator modifications use advanced technology to achieve the required particulate removal, as exemplified by the precharger and large-diameter electrodes. Thus, there is more uncertainty in the precipitator performance of Cases 1, 3, 5, and 6 than in Cases 2

and 4. Other uncertainties affecting costs are the site-specific factors of equipment arrangement, lime supply, and water availability and quality. Uncertainties in the process are associated with reagent stoichiometry, approach temperature, and residence time. These uncertainties raise questions about whether adequate SO_2 removal and spray drying can occur without wetting the precipitator.

In summary, the following conclusions can be drawn about remaining research and development needs at the laboratory and pilot scale:

- The mechanical system design for the most part utilizes commercially available equipment. The only items that pose developmental problems are the two fluid nozzle spray system, the ESP precharger, and the ESP large diameter electrodes.

- From an operating point of view, the greatest concern is adequate spray drying in the (gutted) first field of the ESP to minimize tenacious deposits in the subsequent ESP fields.

- ESP performance on this type of particulate needs to be verified. In particular, the mass loadings and size distribution of the particulate at the end of the spray section, the ESP electrical properties (secondary voltages and currents), and gas distribution device requirements need to be established.

- The capability of a vacuum type flyash handling system to continuously remove hopper material needs to be demonstrated. Additional equipment requirements (for example a delumper to prevent oversize material) need to be defined.

- Retrofit capital costs will be very site specific, particularly if conventional ESP modifications (taller plates or an outlet field) are required.

- The largest single component affecting the operating cost is the reagent consumption. Therefore, process stoichiometry is critical to cost. Also, pebble lime shows a distinct economic advantage over lime hydrate.

- Future research efforts should be concentrated on optimizing the process parameters, in particular, slurry droplet size, Ca/S ratio, approach temperature, and residence time requirements.

- Because of the performance advantages indicated by the precharger and large diameter electrodes, these technologies should be further demonstrated at an appropriate equipment scale.

- Satisfactory operation of the entire E-SOX process needs to be demonstrated on a pilot-scale flue gas sidestream from a coal-fired electric generating plant before proceeding to commercialization of the E-SOX process.

7.0 REFERENCES

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Appendix A
Cost Estimate Details

TABLE A - 1
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 1

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	2,184,590	1,879,720	4,064,310
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	2,264,590	2,003,720	4,268,310
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,409,300	460,300	1,869,600
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	229,320	482,360	711,680
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALS, & FLOW STRAIGHTENING	870,870	1,963,610	2,834,480
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,700,000	1,108,000	2,808,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	0	0	0
TOTAL MECHANICAL WORK	4,209,490	4,014,270	8,223,760
3 ELECTRICAL WORK			
UNIT SWITCHGEAR	175,000	19,120	194,120
MOTOR CONTROL CENTERS	37,280	6,370	43,650
CABLE,CONDUIT,AND CABLE TRAY	106,290	237,740	344,030
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	387,900	395,150	783,050
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$6,861,980	$6,413,140	$13,275,120
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			2,655,000
SUBTOTAL			$15,930,120
CONTINGENCY			3,186,000
TOTAL PLANT INVESTMENT			$19,116,120

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TABLE A - 2
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 2

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	2,184,590	1,879,720	4,064,310
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	2,264,590	2,003,720	4,268,310
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,409,300	460,300	1,869,600
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	229,320	482,360	711,680
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALS, & FLOW STRAIGHTENING	3,592,370	2,407,170	5,999,540
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,700,000	1,108,000	2,808,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	0	0	0
TOTAL MECHANICAL WORK	6,930,990	4,457,830	11,388,820
3 ELECTRICAL WORK			
UNIT SWITCHGEAR	175,000	19,120	194,120
MOTOR CONTROL CENTERS	37,280	6,370	43,650
CABLE,CONDUIT,AND CABLE TRAY	106,290	237,740	344,030
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	387,900	395,150	783,050
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$9,583,480	$6,856,700	$16,440,180
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			3,288,000
SUBTOTAL			19,728,180
CONTINGENCY			3,945,600
TOTAL PLANT INVESTMENT			$23,673,780

TABLE A - 3
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 3

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	2,184,590	1,879,720	4,064,310
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	2,264,590	2,003,720	4,268,310
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,409,300	460,300	1,869,600
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	229,320	482,360	711,680
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALS, & FLOW STRAIGHTENING	1,859,030	3,490,290	5,349,320
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,700,000	1,108,000	2,808,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	0	0	0
TOTAL MECHANICAL WORK	5,197,650	5,540,950	10,738,600
3 ELECTRICAL WORK			
UNIT SWITCHGEAR	175,000	19,120	194,120
MOTOR CONTROL CENTERS	37,280	6,370	43,650
CABLE,CONDUIT,AND CABLE TRAY	106,290	237,740	344,030
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	387,900	395,150	783,050
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$7,850,140	$7,939,820	$15,789,960
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			3,158,000
SUBTOTAL			$18,947,960
CONTINGENCY			3,789,600
TOTAL PLANT INVESTMENT			$22,737,560

TABLE A - 4
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 4

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	2,184,590	1,879,720	4,064,310
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	2,264,590	2,003,720	4,268,310
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,409,300	460,300	1,869,600
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	229,320	482,360	711,680
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALS, & FLOW STRAIGHTENING	1,168,920	1,849,670	3,018,590
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,730,000	1,108,000	2,838,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	0	0	0
TOTAL MECHANICAL WORK	4,537,540	3,900,330	8,437,870
3 ELECTRICAL WORK			
UNIT SWITCHGEAR	175,000	19,120	194,120
MOTOR CONTROL CENTERS	37,280	6,370	43,650
CABLE,CONDUIT,AND CABLE TRAY	106,290	237,740	344,030
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	387,900	395,150	783,050
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$7,190,030	$6,299,200	$13,489,230
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			2,697,800
SUBTOTAL			16,187,030
CONTINGENCY			3,237,400
TOTAL PLANT INVESTMENT			$19,424,430

TABLE A - 5
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 5

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	2,184,590	1,879,720	4,064,310
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	2,264,590	2,003,720	4,268,310
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,409,300	460,300	1,869,600
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	229,320	482,360	711,680
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALS, & FLOW STRAIGHTENING	870,870	1,963,610	2,834,480
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,700,000	1,108,000	2,808,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	0	0	0
TOTAL MECHANICAL WORK	4,209,490	4,014,270	8,223,760
3 ELECTRICAL WORK			
UNIT SUBSTATION & SWITCHGEAR	175,000	19,120	194,120
MOTOR CONTROL CENTERS	37,280	6,370	43,650
CABLE,CONDUIT,AND CABLE TRAY	106,290	237,740	344,030
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	387,900	395,150	783,050
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$6,861,980	$6,413,140	$13,275,120
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			2,655,000
SUBTOTAL			$15,930,120
CONTINGENCY			3,186,000
TOTAL PLANT INVESTMENT			$19,116,120

TABLE A - 6
RETROFIT E-SOx PROCESS (January 1987 Dollars)
CASE - 6

	MATERIAL	LABOR	TOTAL
1 CIVIL/STRUCTURAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC CONVEYING,UNLOADING STATION,STORAGE SILOS,FOUNDATIONS,& SUPPORTS,ATOMIZING AIR COMPRESSOR & CONTROL BUILDING,TRANSFER BLOWER BUILDING, & GENERAL SITEWORK	855,440	773,690	1,629,130
FLYASH SYSTEM - INCLUDES: FOUNDATIONS & SUPPORTS FOR EQUIPMENT AND PIPING	80,000	124,000	204,000
TOTAL CIVIL/STRUCTURAL WORK	935,440	897,690	1,833,130
2 MECHANICAL WORK			
LIME UNLOADING,STORAGE,RECLAIM - INCLUDES: PNEUMATIC PIPING,UNLOADING/ TRANSFER BLOWERS,DISCHARGE BIN ACTIVATORS,SLIDEGATES,ROTARY FEEDERS, TRANSFER BLOWERS,CONVEYING PIPE, ATOMIZING AIR COMPRESSOR,SERVICE & PROCESS PIPE,DIVERTER VALVES,DUST COLLECTORS,VENT FAN & CONTROL PANEL	1,135,200	281,780	1,416,980
SPRAY MODULE CONVERSION TO ESP INCLUDING PNEUMATIC TRANSFER SYSTEM	214,640	436,280	650,920
ESP MODIFICATIONS - INCLUDES: STRUCTURAL & INTERNALRS, & FLOW STRAIGHTENING	870,870	1,963,610	2,834,480
FLYASH SYSTEM - INCLUDES: VACUUM PUMPS,PIPING AND VALVES, FLYASH SILO,DUST COLLECTION EQUIPMENT	1,700,000	1,108,000	2,808,000
SLAKING SYSTEM - INCLUDES: WEIGH FEEDER,SCREW CONVEYOR,CHUTES, BALL MILL,BALL CHARGE,MILL DISCHARGE TANK,CYCLONES,DISTRIBUTOR AND PIPING	550,000	192,000	742,000
TOTAL MECHANICAL WORK	4,470,710	3,981,670	8,452,380
3 ELECTRICAL WORK			
UNIT SWITCHGEAR	187,000	20,080	207,080
MOTOR CONTROL CENTERS	33,430	5,660	39,090
CABLE,CONDUIT,AND CABLE TRAY	106,130	221,990	328,120
COMMUNICATIONS,LIGHTING,GROUNDING AND LIGHTING PROTECTION,AND INSTRUMENTS AND CONTROLS	69,330	131,920	201,250
TOTAL ELECTRICAL WORK	395,890	379,650	775,540
SUBTOTAL - PRESENT DAY CONSTRUCTION COST	$5,802,040	$5,259,010	$11,061,050
ENGINEERING,CONSTRUCTION MANAGEMENT AND OWNERS COST			2,212,200
SUBTOTAL			13,273,250
CONTINGENCY			2,654,700
TOTAL PLANT INVESTMENT			$15,927,950